

UNPUBLISHED PRELIMINARY DATA

THE VAPOR PRESSURE AND LATENT HEAT OF VAPORIZATION
OF p-HYDROGEN FROM THE TRIPLE TO THE CRITICAL POINT

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A B S T R A C T

The existing vapor pressure measurements reported in the literature for p-hydrogen have been utilized to establish the constants of the Frost-Kalkwarf equation applicable between the triple point and the critical point. For refinement, this equation has been applied specifically to vapor pressures above 1 atm. For vapor pressures below 1 atm, a truncated form of this equation has been used. These refined equations, along with the saturated vapor and liquid density relationships of Roder, Diller, Weber, and Goodwin (7) were used with the Clapeyron equation to calculate the latent heats of vaporization. A plot of latent heats of vaporization is presented along with a table of comparison with the values of others.

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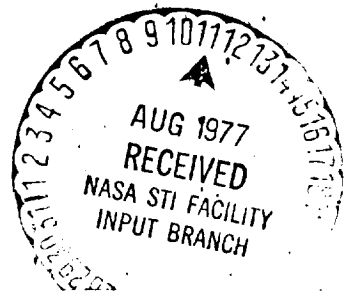
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THE VAPOR PRESSURE AND LATENT HEAT OF VAPORIZATION
OF p-HYDROGEN FROM THE TRIPLE TO THE CRITICAL POINT

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Current interest in the use of p-hydrogen as a fuel for rocket propulsion has stimulated interest for the accurate establishment of several of its physical properties. Two such interdependent properties that have practical usage are the vapor pressure and the latent heat of vaporization. Therefore, this study has been concerned with the procurement from the literature of experimental vapor pressure values to be used for the establishment of an analytical relationship capable of defining accurately the vapor pressure behavior of p-hydrogen from its triple point to its critical point. Furthermore, such a relationship permits the calculation of the latent heat of vaporization of this substance through the use of the Clapeyron equation,

$$\left(\frac{\partial P}{\partial T}\right)_v = \frac{\lambda}{T(v_g - v_l)} \quad (1)$$

Equation (1) is thermodynamically exact and consequently the accuracy of the latent heat of vaporization, λ , depends directly on the ability to obtain accurate values for $(\partial P/\partial T)_v$ and the quantity, $v_g - v_l$.

Vapor-Pressure Behavior. A number of vapor pressure equations are presented in the literature. In a recent critical review, Miller (4) points out the superiority of the Frost-Kalkwarf equation (2) to represent accurately the vapor-pressure behavior of a substance over the complete range included between its triple and critical points. Consequently,

it was decided to apply this equation to the existing vapor pressure measurements presented in the literature. A critical literature survey reveals the extensive experimental vapor pressure measurements of Hoge and Arnold (3), which cover the range from the triple point to the near critical point vicinity. The recent contributions of the National Bureau of Standards (10) cover the range between the normal boiling point and the critical point of p-hydrogen, and also report the triple point value [$T_t = 13.803^\circ\text{K}$, $P_t = 52.82 \text{ mm}$]. In 1963 Barber and Horsford (1) reported experimental measurements from the triple point to the normal boiling point. These three references constitute the basic core of experimental data used to develop the constants of the Frost-Kalkwarf equation,

$$\ln P = A + \frac{B}{T} + C \ln T + D \frac{P}{T^2} \quad (2)$$

In their original development, Frost and Kalkwarf point out that $D = a/R^2$, where a is the pressure van der Waals constant and R is the universal gas constant. The critical constants of p-hydrogen reported by Roder, Diller, Weber, and Goodwin (7) are as follows: $T_c = 32.976 \pm 0.015^\circ\text{K}$, $P_c = 12.759 \pm 0.028 \text{ atm}$, and $\rho_c = 0.01559 \pm 0.00005 \text{ g-moles/cc}$. Thus, the critical volume of p-hydrogen becomes $v_c = 1/0.01559 = 64.144 \text{ cc/g-mole}$. The molecular weight of p-hydrogen reported by Roder et al (7) is $M = 2.01572 \text{ g/g-mole}$. The evaluation of constant D follows directly from the van der Waals constant $a = 27 R^2 T_c^2 / 64 P_c$. Thus,

$$D = \frac{a}{R^2} = \frac{27 T_c^2}{64 P_c} = \frac{27}{64} \frac{(32.976)^2}{(12.759 \times 760)} = 0.047310 (^\circ\text{K})^2/\text{mm}$$

When a reference point (T_1, P_1), selected from a set of data, is substituted into Equation (2), the following expression results:

$$\ln P_1 = A + \frac{B}{T_1} + C \ln T_1 + D \frac{P_1}{T_1^2} \quad (3)$$

By subtracting Equation (3) from Equation (2), and rearranging, it follows that:

$$\frac{\ln \frac{P}{P_1} - D \left[\frac{P}{T^2} - \frac{P_1}{T_1^2} \right]}{\ln \frac{T}{T_1}} = B \frac{\frac{1}{T} - \frac{1}{T_1}}{\ln \frac{T}{T_1}} + C \quad (4)$$

If Equation (2) truly represents the behavior of the vapor pressure function and the reference is reliable, a plot of the vapor pressure modulus,

$$Y = \frac{\ln \frac{P}{P_1} - D \left[\frac{P}{T^2} - \frac{P_1}{T_1^2} \right]}{\ln \frac{T}{T_1}} \quad (5)$$

against the temperature modulus,

$$X = \frac{\frac{1}{T} - \frac{1}{T_1}}{\ln \frac{T}{T_1}} \quad (6)$$

should produce a straight line of slope B and an intercept C. This premise has been substantiated with several substances (6), including the aliphatic hydrocarbons (8,9).

The above procedure was followed in this study using the normal boiling point reported by each experimenter as the reference point for the corresponding set of data. The X and Y values resulting from the data of Hoge and Arnold (3), Weber, Diller, Roder, and Goodwin (10), and Barber and Horsford (1), were plotted as shown in Figure 1. This was done in order to screen out any vapor pressure points that were in significant disagreement with the general trend of the data. Furthermore, this approach would indicate how well the behavior of p-hydrogen conforms to Equation (2), as shown by the linearity of the Y versus X relationship. The

data of the three sources produce a relationship that is linear from the critical point to nearly the triple point. As T approaches T_1 , Equation (6) becomes indeterminate. Application of L'Hospital's rule yields the limiting value $\lim_{T \rightarrow T_1} X = -1/T_1 = -1/20.268 = -0.04934$. Because of the high sensitivity of the vapor pressure modulus, Y , near the reference point, some scatter can be encountered in its vicinity.

The method of least squares was applied to the values of Figure 1 to obtain a slope of $B = -105.651$ and an intercept of $C = 0.425173$ to represent best the data of the three references. The value of $A = 10.4791$ was established by substituting the normal boiling point reported by Weber et al (10), $T_b = 20.268^\circ\text{K}$, into Equation (2), along with the already established values for B , C , and D . The final equation for p-hydrogen over the complete range included between the triple and critical points becomes:

$$\ln P = 10.4791 - \frac{105.651}{T} + 0.425173 \ln T + 0.047310 \frac{P}{T^2} \quad (7)$$

where P is in millimeters of mercury and T is in degrees Kelvin. Vapor pressures calculated with Equation (7) are presented in Table I along with the corresponding experimental values and resulting deviations. Each point is identified in this table by B for Barber and Hosford (1), H for Hoge and Arnold (3), and W for Weber et al (10). These calculations were carried out by an iterative scheme on an IBM 709 digital computer. These iterations were carried out until the correction between successive values of P was less than 0.01 mm.

Despite the fact that Equation (7) is capable of producing vapor pressures well within ordinary limits of accuracy, it was felt that improvements could be made to represent more precisely the vapor pressure behavior of p-hydrogen.

As has already been mentioned, the values in the low pressure

region of the Y - X relationship are slightly offset from the otherwise straight line. On the basis of this observation, it was decided to fit this low pressure region with a separate vapor pressure-temperature relationship. Therefore, a new straight line was fitted through the (Y , X) values corresponding to vapor pressures above one atmosphere and placing more weight to the values in the high pressure region. Again the method of least squares was applied to produce a slope of $B = -110.157$ and an intercept of $C = 0.240055$. Constant A was determined using the vapor pressure value of Weber et al (10), $T = 29.000^\circ\text{K}$ and $P = 6.8863 \text{ atm (5233.6 mm)}$. This procedure yielded $A = 11.2586$. Therefore, the vapor pressure equation for the high pressure range becomes,

$$\ln P = 11.2586 - \frac{110.157}{T} + 0.240055 \ln T + 0.047310 \frac{P}{T^2} \quad (8)$$

Vapor pressures calculated with Equation (8) are presented in Table II along with the corresponding experimental values and their deviations. It will be noted that these deviations remain small for pressures down to the normal boiling point and then increase to a maximum value of 4.52 percent at the triple point. In view of this, the application of Equation (8) should be restricted to vapor pressures above 760 mm of mercury.

Since the last term of Equation (2) accounts for the reversal in curvature of the $\ln P$ versus $1/T$ relationship in the vicinity of the critical point (9), it becomes unnecessary to carry it along for the establishment of a vapor pressure relationship in the low pressure region. Therefore, the truncated form of Equation (2) becomes,

$$\ln P = A + \frac{B}{T} + C \ln T \quad (9)$$

Again, a reference point (P_1 , T_1) is chosen and substituted into Equation (9). The resulting equation is then subtracted from Equation (9)

and rearranged to yield the expression,

$$\frac{\ln \frac{P}{P_1}}{\frac{1}{T} - \frac{1}{T_1}} = B + C \frac{\ln \frac{T}{T_1}}{\frac{1}{T} - \frac{1}{T_1}} \quad (10)$$

The reference point selected for this procedure was again the normal boiling point.

The vapor pressure modulus, $Q = (\ln P/P_1)/(\frac{1}{T} - \frac{1}{T_1})$ was plotted against the temperature modulus $S = (\ln T/T_1)/(\frac{1}{T} - \frac{1}{T_1})$ as shown in Figure 2. The fact that the Q - S relationship is linear in the low pressure region and curved in the high pressure region supports the assumption that the term DP/T^2 is negligible at low pressures. Application of L'Hospital's rule to the temperature modulus yields $\lim_{T \rightarrow T_1} (\ln T/T_1)/(\frac{1}{T} - \frac{1}{T_1}) = -T = -20.268$. The method of least squares was applied to the values from the triple point to the normal boiling point. The results of this analysis produced an intercept $B = -87.2596$ and a slope of $C = 1.69482$. The normal boiling point was then used to determine constant $A = 5.83882$. Thus the vapor pressure function for p-hydrogen covering the range from the triple point to the normal boiling point becomes,

$$\ln P = 5.83882 - \frac{87.2596}{T} + 1.69482 \ln T \quad (11)$$

Values calculated with Equation (11), along with corresponding experimental values and deviations are presented in Table III. A review of these comparisons indicates that Equation (11) is capable of predicting accurate vapor pressures up to almost 1400 mm. Since the objective of Equation (11) is to define the vapor pressure behavior of p-hydrogen up to the boiling point, this equation more than fulfills its purpose. Therefore, the combined results of Equation (11) and Equation (8) enable the calculation of accurate vapor pressures from the triple point to

the critical point. At the normal boiling point, these equations properly blend into each other as indicated by their derivatives at this point. For Equation (8), $dP/dT = 226.0 \text{ mm/}^\circ\text{K}$, and for Equation (11), $dP/dT = 225.0 \text{ mm/}^\circ\text{K}$.

LATENT HEATS OF VAPORIZATION

Equations (8) and (11) have been used to obtain values of the slope, dP/dT , along the vapor-pressure curve. For pressures above the normal boiling point, the differentiated form of Equation (8),

$$\frac{dP}{dT} = \frac{0.240055/T + 110.157/T^2 + 0.094620 P/T^3}{1/P - 0.047310/T^2} \quad (12)$$

was used to calculate these slopes at convenient temperature intervals. From the triple point up to and including the normal boiling point, the differentiated form of Equation (11),

$$\frac{dP}{dT} = \frac{P}{T} \left[1.69482 + \frac{87.2596}{T} \right] \quad (13)$$

was used to obtain the values of the slopes at convenient intervals. The saturated vapor and liquid molar volumes, v_g and v_l , respectively, were obtained from the saturated density relationships of Roder et al (7), which were developed from their experimental studies. Using this information, the latent heats of vaporization for p-hydrogen were calculated from the rearranged Clapeyron equation,

$$\lambda = (v_g - v_l) T \frac{dP}{dT} \quad (14)$$

The resulting latent heats of vaporization in $\text{cm}^3 \text{ mm/g-mole}$ were divided by the conversion factors 760 mm/atm and $41.2929 \text{ cm}^3 \text{ atm/cal}$ to produce values in cal/g-mole . Values of slopes, saturated vapor and liquid molar volumes, and latent heats of vaporization are presented

for convenient temperatures in Table IV. These calculated latent heats of vaporization have been plotted to produce Figure 3. It will be noted in this figure that the latent heat function of p-hydrogen reaches a maximum at approximately 17.0°K.

To compare these results with the experimental latent heats of vaporization of White, Hu, and Johnston (11), values were calculated at their corresponding experimental temperatures. These comparisons are presented in Table V. Also included in this table are the calculated values of Mullins, Ziegler, and Kirk (5) and Roder et al (7).

The latent heats of vaporization of this investigation presented in Table V show a good agreement when compared with the experimental and calculated values reported by others (5,7,11). Mullins, Ziegler, and Kirk (5) calculated latent heats of vaporization from the triple point up to and including 22.0°K using a virial type equation of state. The only experimental values are presented by White, Hu, and Johnston (11) for temperatures above the normal boiling point. The values reported by Roder, Diller, Weber, and Goodwin (7) were calculated using the Clapeyron equation and three separate vapor pressure relationships applicable in different regions included between the triple point and the critical point. The values resulting from this study also cover the complete vapor-liquid range and were found to be in good agreement with those already reported in the literature. These findings add creditability to the work already cited (5,7,11) in which the approach utilized to calculate the latent heat of vaporization of p-hydrogen differed in each case.

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NOMENCLATURE

a	van der Waals constant, $(\text{cm}^3/\text{g-mole})^2 \text{ atm}$
A,B,C,D	constants for Frost-Kalkwarf equation, Equation (2)
M	molecular weight
P	vapor pressure, mm of mercury
P_1	vapor pressure of reference point, mm of mercury
P_c	critical pressure, atm
P_t	triple point pressure, mm of mercury
Q	vapor pressure modulus, $(\ln P/P_1)/(1/T - 1/T_1)$
R	gas constant
S	temperature modulus, $(\ln T/T_1)/(1/T - 1/T_1)$
T	temperature, °K
T_1	temperature of reference point, °K
T_b	normal boiling point, °K
T_c	critical temperature, °K
T_t	triple point temperature, °K
v_c	critical volume, $\text{cm}^3/\text{g-mole}$
v_g	molar volume of saturated vapor, $\text{cm}^3/\text{g-mole}$
v_l	molar volume of saturated liquid, $\text{cm}^3/\text{g-mole}$
X	temperature modulus, $(1/T - 1/T_1)/(\ln T/T_1)$
Y	vapor pressure modulus, $\{ \ln P/P_1 - D(P/T^2 - P_1/T_1^2) \} / (\ln T/T_1)$
Greek	
λ	latent heat of vaporization, cal/g-mole
ρ_c	critical density, g-moles/ cm^3

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TABLE 1. COMPARISON OF EXPERIMENTAL AND CALCULATED VAPOR PRESSURES OF p-HYDROGEN USING EQUATION (7)

$$\ln P = 10.4791 - \frac{105.651}{T} + 0.425173 \ln T + 0.047310 \frac{P}{T^2}$$

millimeters of mercury						millimeters of mercury					
	T, °K	P _{exptl}	P _{calc}	ΔP	Dev. %		T, °K	P _{exptl}	P _{calc}	ΔP	Dev. %
W	32.976*	9696.8	9762.3	65.5	0.68	H	24.440	2189.4	2182.1	-7.3	-0.33
W	32.900	9589.6	9654.0	64.4	0.67	H	23.634	1827.1	1822.4	-4.7	-0.26
H	32.883	9566.2	9630.4	64.2	0.67	W	23.000	1572.3	1570.6	-1.7	-0.11
H	32.884	9564.4	9630.8	66.4	0.69	H	22.896	1534.9	1531.7	-3.2	-0.21
H	32.883	9559.3	9629.4	70.1	0.73	H	22.569	1416.1	1414.3	-1.8	-0.13
W	32.800	9449.5	9513.1	63.6	0.67	H	22.270	1313.8	1312.4	-1.4	-0.10
W	32.700	9312.0	9373.8	61.8	0.66	H	22.250	1308.4	1306.0	-2.4	-0.19
H	32.636	9219.5	9285.2	65.7	0.71	W	22.000	1225.4	1225.1	-0.3	-0.02
W	32.600	9176.8	9236.2	59.4	0.65	H	21.677	1127.2	1126.3	-0.9	-0.08
W	32.500	9042.8	9100.2	57.4	0.63	H	21.328	1026.8	1025.8	-1.0	-0.10
H	32.375	8875.1	8932.8	57.7	0.65	H	21.195	989.8	989.2	-0.6	-0.06
H	32.129	8557.7	8609.6	51.9	0.61	H	20.943	922.5	922.7	0.2	0.03
W	32.000	8399.0	8443.6	44.6	0.53	H	20.941	922.1	922.2	0.1	0.01
W	31.881	8255.1	8293.0	37.9	0.46	H	20.855	900.7	900.3	-0.4	-0.05
W	31.500	7792.5	7824.7	32.2	0.41	H	20.507	815.2	815.0	-0.2	-0.03
H	31.392	7660.2	7695.8	35.6	0.46	H	20.502	813.7	813.8	0.1	0.01
W	31.072	7302.5	7323.1	20.6	0.28	H	20.397	789.6	789.3	-0.3	-0.03
W	31.000	7221.1	7241.2	20.1	0.28	B	20.270	760.0	760.6	0.6	0.07
H	30.892	7102.8	7119.7	16.9	0.24	H	20.268	760.0	760.0	0.0	0.00
W	30.500	6679.2	6691.5	12.3	0.18	W	20.268	760.0	760.0	0.0	0.00
W	30.368	6544.6	6551.3	6.7	0.10	H	20.255	757.1	757.0	-0.1	-0.01
W	30.000	6169.0	6173.6	4.6	0.07	H	20.030	707.7	707.9	0.2	0.03
H	29.907	6080.2	6081.0	0.8	0.01	H	19.114	530.7	531.2	0.5	0.09
H	29.386	5583.9	5578.9	-5.0	-0.09	B	19.050	519.5	520.1	0.6	0.11
W	29.000	5233.6	5227.9	-5.7	-0.11	H	18.571	442.1	442.8	0.7	0.16
H	28.870	5121.5	5113.0	-8.5	-0.17	B	18.447	423.3	424.2	0.9	0.23
H	28.376	4705.7	4694.2	-11.5	-0.24	H	17.819	338.4	338.7	0.3	0.10
W	28.000	4401.9	4392.8	-9.1	-0.21	B	17.429	291.3	292.3	1.0	0.36
H	27.864	4299.6	4287.5	-12.1	-0.28	H	16.965	243.1	243.6	0.5	0.19
H	27.398	3952.7	3939.5	-13.2	-0.33	H	16.945	241.4	241.6	0.2	0.07
W	27.000	3669.7	3658.7	-11.0	-0.30	B	16.288	181.0	183.5	2.5	1.35
H	26.771	3517.5	3504.0	-13.5	-0.38	H	15.831	149.7	149.6	-0.1	-0.04
H	26.188	3142.6	3131.0	-11.6	-0.37	B	15.348	119.4	119.2	-0.2	-0.16
W	26.000	3026.7	3017.0	-9.7	-0.32	B	15.005	100.0	100.0	-0.3	-0.27
H	25.885	2960.3	2949.1	-11.2	-0.38	B	14.524	70.0	70.0	-0.4	-0.47
H	25.561	2773.5	2762.5	-11.0	-0.40	B	13.977	50.3	57.7	-0.6	-0.97
H	25.037	2488.5	2479.2	-9.3	-0.37	B	13.816*	52.95	52.5	-0.4	-0.77
W	25.000	2467.1	2459.9	-7.2	-0.29	W	13.803*	52.82	52.1	-0.7	-1.29
H	24.890	2414.1	2403.6	-10.5	-0.44	H	13.803	52.80	52.1	-0.7	-1.25

* reported critical point
 * reported triple point

TABLE 11. COMPARISON OF EXPERIMENTAL AND CALCULATED VAPOR PRESSURES OF p-HYDROGEN USING EQUATION (8)

$$\ln P = 11.2586 - \frac{110.157}{T} + 0.240055 \ln T + 0.047310 \frac{P}{T^2}$$

millimeters of mercury					millimeters of mercury				
T, °K	P _{exptl}	P _{calc}	ΔP	Dev. %	T, °K	P _{exptl}	P _{calc}	ΔP	Dev. %
W 32.976*	9696.8	9690.2	-6.6	-0.07	H 24.440	2189.4	2191.2	1.8	0.08
W 32.900	9589.6	9585.0	-4.6	-0.05	H 23.634	1827.1	1829.6	2.5	0.14
H 32.883	9566.2	9561.9	-4.3	-0.04	W 23.000	1572.3	1576.3	4.0	0.26
H 32.884	9564.4	9562.4	-2.0	-0.02	H 22.896	1534.9	1537.2	2.3	0.15
H 32.883	9559.3	9561.0	1.7	-0.02	H 22.569	1416.1	1419.0	2.9	0.20
W 32.800	9449.5	9447.8	-1.7	-0.02	H 22.270	1313.8	1316.5	2.7	0.20
W 32.700	9312.0	9312.2	0.2	0.00	H 22.250	1308.4	1310.0	1.6	0.12
H 32.636	9219.5	9225.8	6.3	0.07	W 22.000	1225.4	1228.6	3.2	0.26
W 32.600	9176.8	9178.1	1.3	0.01	H 21.677	1127.2	1129.0	1.8	0.16
W 32.500	9042.8	9045.4	2.6	0.03	H 21.328	1026.8	1027.8	1.0	0.10
H 32.375	8875.1	8882.1	7.0	0.08	H 21.195	989.8	990.9	1.1	0.11
H 32.129	8557.7	8566.3	8.6	0.10	H 20.943	922.5	924.0	1.5	0.16
W 32.000	8399.0	8403.9	4.9	0.06	H 20.941	922.1	923.5	1.4	0.15
H 31.881	8255.1	8256.5	1.4	0.02	H 20.855	900.7	901.4	0.7	0.08
W 31.500	7792.5	7797.3	4.8	0.06	H 20.507	815.2	815.5	0.3	0.03
H 31.392	7660.2	7670.8	10.6	0.14	H 20.502	813.7	814.3	0.6	0.07
H 31.074	7302.5	7304.5	2.0	0.03	H 20.397	789.6	789.7	0.1	0.01
W 31.000	7221.1	7223.9	2.8	0.04	B 20.270	760.0	760.7	0.7	0.09
H 30.892	7102.8	7104.2	1.4	0.02	H 20.268	760.0	760.1	0.1	0.01
W 30.500	6679.2	6682.2	3.0	0.04	W 20.268	760.0	760.1	0.1	0.01
H 30.368	6544.6	6543.8	-0.8	-0.01	H 20.255	757.1	757.1	0.0	0.00
W 30.000	6169.0	6170.7	1.7	0.03	H 20.030	707.7	707.7	0.0	0.00
H 29.907	6030.2	6079.1	-1.1	-0.02	H 19.114	530.7	529.8	-0.9	-0.17
H 29.386	5583.9	5581.8	-2.1	-0.04	B 19.050	519.5	518.7	-0.8	-0.16
W 29.000	5233.6	5233.6	0.0	0.00	H 18.571	442.1	440.9	-1.2	-0.27
H 28.870	5121.5	5119.5	-2.0	-0.04	B 18.447	423.3	422.3	-1.0	-0.24
H 28.376	4705.7	4703.2	-2.5	-0.05	H 17.819	338.4	336.4	-2.0	-0.59
W 28.000	4401.9	4403.1	1.2	0.03	B 17.429	291.3	289.9	-1.4	-0.49
H 27.864	4299.6	4298.2	-1.4	-0.03	H 16.965	243.1	241.0	-2.1	-0.87
H 27.393	3952.7	3951.1	-1.6	-0.04	H 16.945	241.4	239.0	-2.4	-1.00
W 27.000	3669.7	3670.7	1.0	0.03	B 16.288	181.0	180.9	-0.1	-0.08
H 26.771	3517.5	3516.0	-1.5	-0.04	H 15.831	149.7	147.1	-2.6	-1.72
H 26.188	3142.6	3142.9	0.3	0.01	B 15.348	119.4	116.8	-2.6	-2.14
W 26.000	3026.7	3028.7	2.0	0.07	B 15.005	100.8	98.3	-2.5	-2.50
H 25.885	2960.3	2960.7	0.4	0.01	B 14.524	78.6	76.2	-2.4	-3.03
H 25.561	2773.5	2773.7	0.2	0.01	B 13.977	58.3	55.9	-2.4	-4.05
H 25.037	2488.5	2489.6	1.1	0.04	B 13.816*	52.95	50.8	-2.1	-4.01
W 25.000	2467.1	2470.1	3.0	0.12	W 13.803*	52.82	50.4	-2.4	-4.52
H 24.890	2414.1	2413.6	-0.5	-0.02	H 13.803*	52.80	50.4	-2.4	-4.49

* reported critical point

* reported triple point

TABLE III. COMPARISON OF EXPERIMENTAL AND CALCULATED VAPOR PRESSURES
OF p-HYDROGEN USING EQUATION (11)

$$\ln P = 5.83882 - \frac{87.2596}{T} + 1.69482 \ln T$$

millimeters of mercury					
	T, °K	P _{exptl}	P _{calc}	ΔP	Dev. %
H	13.803*	52.80	52.76	-0.04	-0.08
W	13.803*	52.82	52.76	-0.06	-0.11
B	13.816*	52.95	53.16	0.21	0.39
B	13.977	52.28	58.30	0.02	0.03
B	14.524	78.62	78.70	0.08	0.10
B	15.005	100.84	100.87	0.02	0.02
B	15.348	119.38	119.36	-0.01	-0.01
H	15.831	149.70	149.62	-0.08	-0.05
B	16.288	181.03	183.28	2.25	1.24
H	16.945	241.40	241.17	-0.23	-0.10
H	16.965	243.10	243.15	0.05	0.02
B	17.429	291.29	291.81	0.52	0.18
H	17.819	338.40	338.15	-0.25	-0.07
B	18.447	423.28	423.65	0.37	0.08
H	18.571	442.10	442.21	0.11	0.02
B	19.050	519.53	519.63	0.10	0.02
H	19.114	530.70	530.70	0.00	0.00
H	20.030	707.70	707.81	0.11	0.02
H	20.255	757.10	757.03	-0.07	-0.01
W	20.268	760.00	760.00	0.00	0.00
H	20.268	760.00	760.00	0.00	0.00
B	20.270	760.00	760.56	0.56	0.07
H	20.397	789.60	789.40	-0.20	-0.02
H	20.502	813.70	813.91	0.21	0.02
H	20.507	815.20	815.07	-0.13	-0.02
H	20.855	900.70	900.57	-0.13	-0.01
H	20.941	922.10	922.54	0.44	0.05
H	20.943	922.50	923.08	0.58	0.06
H	21.195	989.80	989.60	-0.20	-0.02
H	21.328	1026.8	1026.2	-0.6	-0.05
H	21.677	1127.2	1126.8	-0.4	-0.03
W	22.000	1225.4	1225.7	0.3	0.02
H	22.250	1308.4	1306.4	-2.0	-0.15
H	22.270	1313.8	1312.9	-0.9	-0.07
H	22.569	1416.1	1414.5	-1.5	-0.11
H	22.896	1534.9	1531.6	-3.3	-0.22

* reported triple point

TABLE IV. DERIVED QUANTITIES USED TO CALCULATE LATENT HEATS OF VAPORIZATION

T, °K	P, mm	cm ³ /g-mole		dP/dT		λ cal/g-mole	T, °K	P, mm	cm ³ /g-mole		dP/dT		λ cal/g-mole
		v_g	v_l	atm/°K					v_g	v_l	atm/°K		
13.803*	52.8	16,025	26.173	0.0403		215.6	29.200	5412.0	217.97	35.910	1.1892		153.1
14.000	59.1	14,503	26.230	0.0440		216.0	29.300	5503.0	213.64	36.076	1.2035		151.6
14.500	77.7	11,378	26.376	0.0544		216.8	29.400	5595.0	209.38	36.247	1.2179		150.1
15.000	100.6	9055.3	26.526	0.0663		217.4	29.500	5688.1	205.19	36.423	1.2325		148.6
15.500	128.3	7301.9	26.682	0.0798		217.9	29.600	5782.3	201.06	36.604	1.2472		147.0
16.000	161.4	5959.5	26.842	0.0949		218.2	29.700	5877.7	197.00	36.789	1.2620		145.4
16.500	200.6	4917.7	27.008	0.1117		218.4	29.800	5974.1	193.00	36.931	1.2760		143.8
17.000	246.6	4098.8	27.179	0.1303		218.4	29.900	6071.8	189.05	37.178	1.2919		142.1
17.500	299.9	3447.5	27.357	0.1507		218.4	30.000	6170.5	185.16	37.380	1.3071		140.4
18.000	361.3	2923.7	27.542	0.1728		218.2	30.100	6270.4	181.33	37.590	1.3225		138.6
18.500	431.5	2498.1	27.734	0.1968		217.8	30.200	6371.5	177.55	37.806	1.3379		136.7
19.000	511.1	2149.0	27.933	0.2225		217.2	30.300	6473.8	173.82	38.030	1.3535		134.9
19.500	600.8	1860.1	28.141	0.2501		216.4	30.400	6577.3	170.13	38.261	1.3692		132.9
20.000	701.4	1619.1	28.358	0.2795		215.4	30.500	6681.9	166.49	38.501	1.3851		130.9
20.268	760.0	1506.8	28.479	0.2960		214.8	30.600	6787.8	162.89	38.749	1.4011		128.9
							30.700	6894.9	159.34	39.008	1.4172		126.8
20.500	813.8	1417.1	28.586	0.3123		215.3	30.800	7003.2	155.82	39.277	1.4335		124.6
21.000	938.8	1245.3	28.824	0.3456		213.8	30.900	7112.8	152.33	39.557	1.4500		122.4
21.500	1076.8	1098.8	29.073	0.3809		212.2	31.000	7223.6	148.88	39.849	1.4666		120.0
22.000	1228.5	973.39	29.335	0.4181		210.3	31.100	7335.7	145.45	40.155	1.4833		117.6
22.500	1394.8	865.34	29.612	0.4573		208.2	31.200	7449.1	142.05	40.476	1.5002		115.1
23.000	1576.3	771.82	29.903	0.4984		206.0	31.300	7563.8	138.67	40.813	1.5173		112.6
23.500	1773.8	690.48	30.212	0.5415		203.5	31.400	7679.7	135.31	41.168	1.5345		109.9
24.000	1988.1	619.37	30.539	0.5866		200.8	31.500	7797.0	131.96	41.543	1.5518		107.0
24.500	2219.9	556.93	30.887	0.6338		197.8	31.600	7915.6	128.62	41.931	1.5695		104.1
25.000	2470.1	501.84	31.259	0.6832		194.6	31.700	8035.6	125.29	42.365	1.5872		101.0
25.500	2739.4	453.04	31.656	0.7346		191.2	31.800	8156.9	121.94	42.818	1.6051		97.81
26.000	3028.7	409.62	32.084	0.7883		187.4	31.900	8279.6	118.59	43.305	1.6232		94.40
26.500	3338.8	370.81	32.545	0.8442		183.3	32.000	8403.6	115.21	43.832	1.6414		90.79
27.000	3670.6	336.00	33.045	0.9025		178.8	32.100	8529.1	111.79	44.406	1.6599		86.95
27.250	3844.9	319.91	33.311	0.9325		176.4	32.200	8655.9	108.32	45.038	1.6785		82.83
27.500	4025.0	304.62	33.590	0.9632		173.9	32.300	8784.2	104.78	45.742	1.6973		78.38
27.750	4211.0	290.08	33.882	0.9945		171.2	32.400	8913.9	101.13	46.536	1.7163		73.52
28.000	4402.9	276.24	34.188	1.0264		168.5	32.500	9045.1	97.334	47.452	1.7355		68.14
28.250	4601.0	263.03	34.510	1.0590		165.6	32.600	9177.7	93.315	48.538	1.7549		62.04
28.500	4805.4	250.43	34.850	1.0923		162.5	32.700	9311.8	88.955	49.884	1.7745		54.90
28.750	5016.2	238.38	35.208	1.1263		159.3	32.800	9447.5	83.969	51.687	1.7944		46.01
29.000	5233.4	226.85	35.588	1.1609		155.9	32.900	9584.6	77.567	54.571	1.8144		33.24
29.100	5322.2	222.37	35.747	1.1750		154.5	32.976*	9689.8	64.144	64.144	1.8298		0.00

* triple point

† critical point

TABLE V. COMPARISON OF LATENT HEATS OF VAPORIZATION RESULTING FROM THIS STUDY
WITH EXPERIMENTAL AND CALCULATED VALUES OF OTHERS

T, °K	λ , calories/g-mole			
	This Study	White et al (11)*	Mullins et al (5)	Roder et al (7)
13.803	215.6	-	216.87	216.8
13.990	216.0	-	217.07	217.1
14.000	216.0	-	-	217.1
14.990	217.4	-	217.93	218.3
15.000	217.4	-	-	218.3
15.990	218.2	-	218.44	218.6
16.000	218.2	-	-	218.5
16.990	218.4	-	218.50	218.4
17.000	218.4	-	-	218.4
17.990	218.2	-	218.05	217.9
18.000	218.2	-	-	217.9
18.990	217.2	-	217.03	216.8
19.000	217.2	-	-	216.8
19.990	215.4	-	215.38	215.3
20.000	215.4	-	-	215.2
20.268	214.8	-	214.80 [‡]	214.8 [‡]
21.000	213.8	-	214.03	212.5
22.000	210.3	-	209.94	209.5
23.000	206.0	-	-	205.6
24.000	200.8	-	-	200.8
24.41	198.4	204.7	-	198.5
25.000	194.6	-	-	195.0
26.000	187.4	-	-	187.8
26.33	184.7	193.4	-	185.2
27.000	178.8	-	-	178.2
28.000	168.5	-	-	168.0
28.12	167.1	177.5	-	167.0
29.000	155.9	-	-	155.3
29.65	146.2	145.2	-	145.9
30.000	140.4	-	-	140.1
30.97	120.8	116.5	-	120.5
31.000	120.0	-	-	119.8
31.85	96.13	93.8	-	96.1
32.000	90.79	-	-	90.8
32.400	73.52	-	-	73.9
32.69	55.67	51.8	-	55.4
32.700	54.90	-	-	55.6
32.900	33.24	-	-	33.9

* recalculated by Roder et al (7) as suggested by White et al (11)

[‡] defined by Roder et al (7)

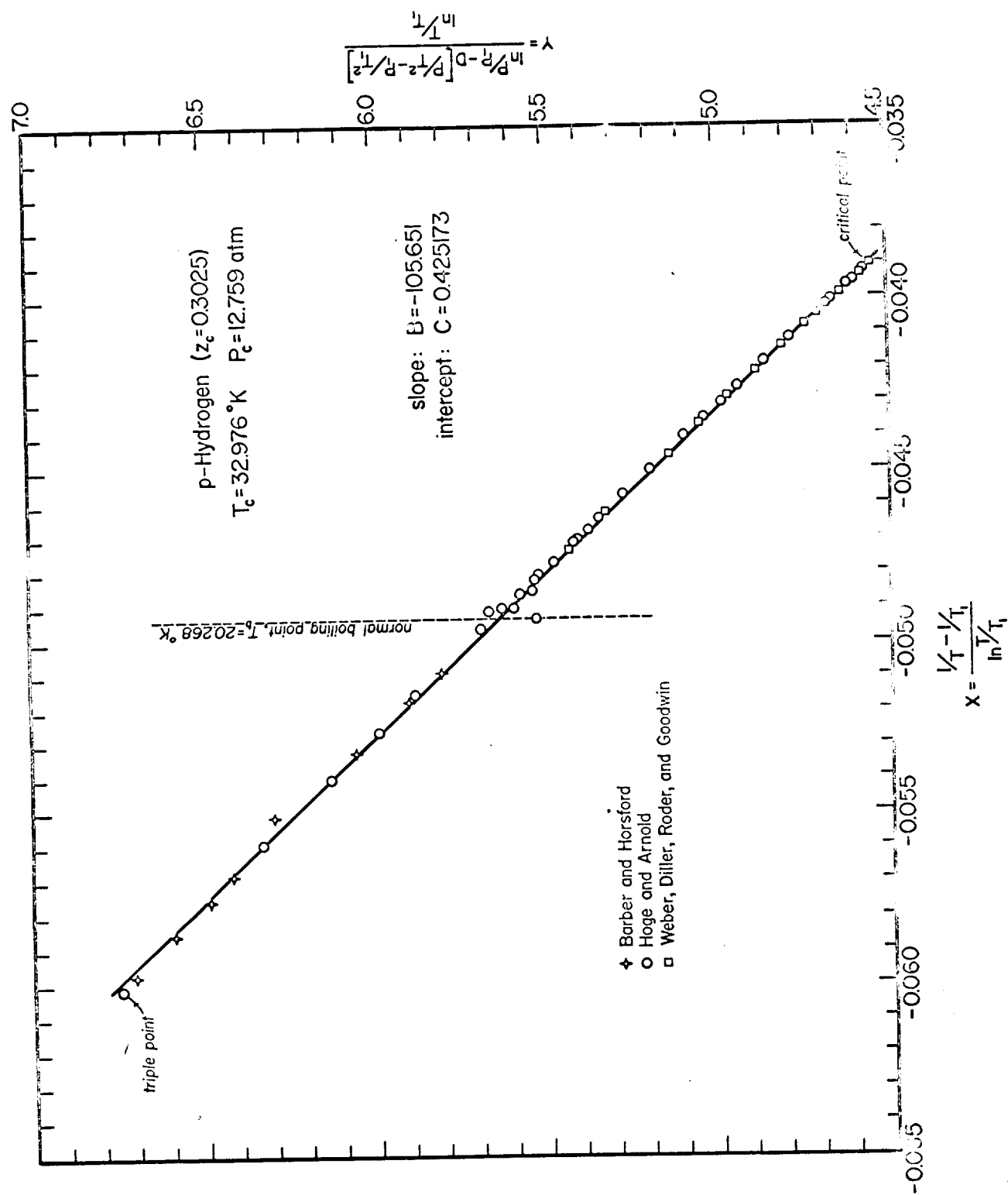


Figure 1. Relationship between Y and X for p-hydrogen

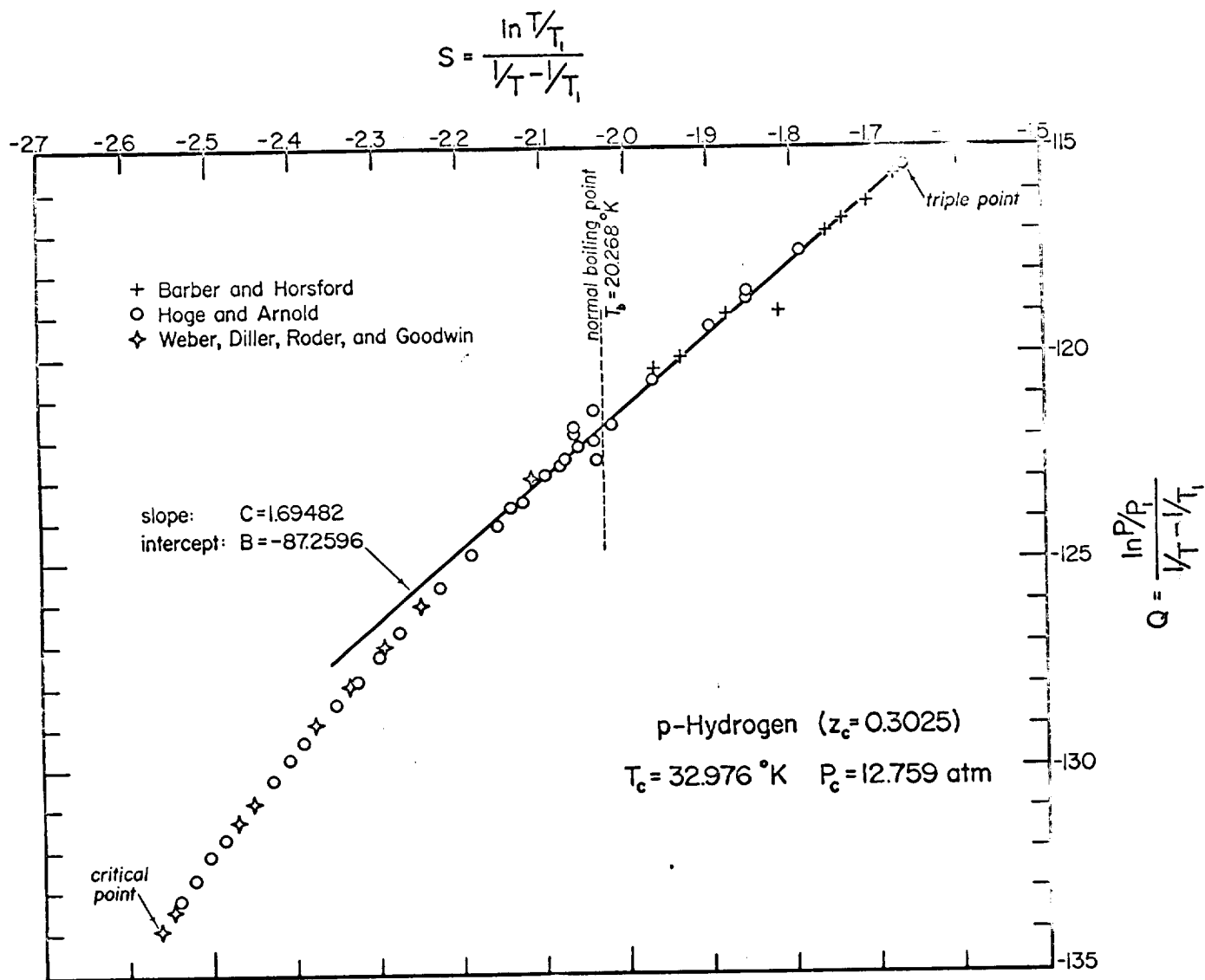


Figure 2. Relationship between Q and S for p-hydrogen

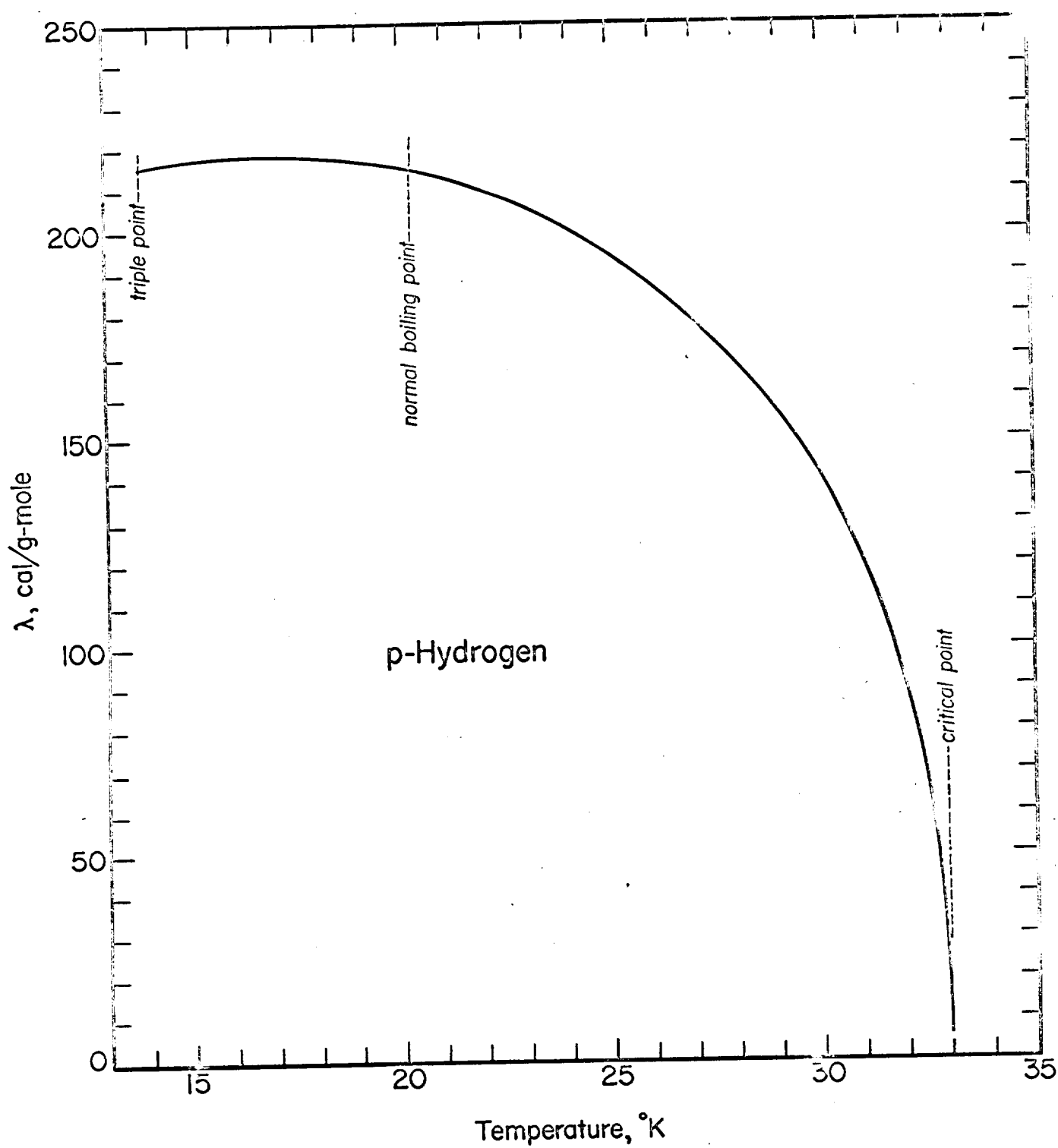


Figure 3. Latent heat of vaporization for p-hydrogen.